Diclofenac Toxicity to Hepatocytes: A Role for Drug Metabolism in Cell Toxicity¹

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ABSTRACT

Diclofenac, a 2-arylacetic acid, nonsteroidal anti-inflammatory drug, has been reported to cause adverse hepatic effects in certain individuals. To discriminate among possible mechanisms of hepatotoxicity, we examined the effects of diclofenac on human and rat hepatocytes and hepatic cell lines (HepG2, FaO), investigated the major biochemical events in the course of diclofenac cytotoxicity (calcium homeostasis, lipid peroxidation, and mitochondrial dysfunction), and investigated whether cytotoxicity could be related to drug metabolism by cytochrome P-450. Acute diclofenac-induced toxicity in hepatocytes was precluded by a decrease in ATP levels, whereas no significant oxidative stress (decrease in glutathione and lipid peroxidation) or increase in intracellular calcium concentration could be observed at early incubation stages. Diclofenac was more cytotoxic to drug metabolizing cells (rat and human primary cultured hepatocytes) than to nonmetabolizing cell lines (HepG2, FaO). Despite the fact that diclofenac itself was effective in impairing ATP synthesis by mitochondria, we found evidence that toxicity was also related to drug metabolism and was reduced by the addition of cytochrome P-450 inhibitors (proadifen and ketoconazole) to culture medium. The in vitro cytotoxicity correlated well with the formation by hepatocytes of 5-hydroxydiclofenac and, in particular, N,5-dihydroxydiclofenac, a minor metabolite first characterized in this article. Hepatic microsomes showed the ability to both oxidize 5-hydroxydiclofenac to N,5-dihydroxydiclofenac and back reduce the latter to 5-hydroxydiclofenac with the consumption of NADPH. The experimental results suggest that the toxic effect of diclofenac on hepatocytes may be caused by drug-induced mitochondrial impairment, together with a futile consumption of NADPH.

Diclofenac is a frequently prescribed nonsteroidal anti-inflammatory drug. Although diclofenac-associated hepatitis was thought to be rare, there are clinical reports of severe hepatic reactions associated with their use (Helfgott et al., 1990; Sallie, 1990; Scully et al., 1993). In vitro experiments with cultured rat hepatocytes have shown, however, that the covalent binding of diclofenac to hepatic proteins have been invoked to explain its toxicity. Diclofenac was found to generate protein adducts (Pumford et al., 1994), the clinical findings in other patients appear to be more consistent with a direct toxic effect of the drug or a drug metabolite (Helfgott et al., 1990; Iveson et al., 1990; Sallie, 1990; Scully et al., 1993).

The mechanism by which diclofenac causes liver alterations in certain individuals is not yet fully understood, and both the formation of a toxic metabolite and covalent binding of the drug to hepatic proteins have been invoked to explain its toxicity. Diclofenac was found to generate protein adducts in the livers of treated mice as well as in rat hepatocytes via protein acylation by the drug glucuronide (Pumford et al., 1993). In vitro experiments with cultured rat hepatocytes have shown, however, that the covalent binding of diclofenac is neither the only nor the major cause of acute cytotoxicity (Kretz-Rommel and Boelsterli, 1993). Moreover, previous work has suggested that diclofenac is cytotoxic to rat hepatocytes after cytochrome P-450 (CYP)-mediated metabolism (Schmitz et al., 1992; Jurima-Romet et al., 1994). Recently, the formation of reactive metabolite(s) by drug oxidation,
which could be related to drug toxicity, has been reported (Miymoto et al., 1997).

Diclofenac undergoes hepatic metabolism both in rat and human hepatocytes, and the main biotransformation reactions (aromatic hydroxylations and conjugations at various sites of the molecule) are common to several animal species (Riess et al., 1978; Stierling et al., 1979). In human liver microsomes, the major oxidative metabolic pathway is the formation of 4'-hydroxydiclofenac (4'-OHdic) by CYP2C9 (Smith and Jones, 1992; Leemann et al., 1993). Formation of 5-hydroxydiclofenac (5-OHdic), 3'-hydroxydiclofenac, 4',5'-dihydroxydiclofenac, and 3'-hydroxy-4'-methoxydiclofenac has also been reported in humans, but to a much lesser extent (Riess et al., 1978; Faigle et al., 1988). In the rat, 4'-OHdic together with 5-OHdic are the major urine metabolites (Stierling et al., 1979).

We have investigated the acute effects of diclofenac on the viability and functionality of cultured hepatocytes to discriminate between possible mechanisms of toxicity and found that a decrease in ATP levels preluded cell death. Despite the fact that diclofenac itself was effective in impairing ATP synthesis by mitochondria, we found evidence that toxicity was also related to drug metabolism, in particular with the formation of 5-OHdic and N7,5,6-dihydroxydiclofenac (N7,5-OH2dic). Both metabolites can easily interchange by oxidation and reduction and both cause a continuous consumption of NADPH. Thus, in addition to the effects of diclofenac and its major metabolites on mitochondrial function, the existence of a futile red-ox cycle could also contribute to the mechanism of toxicity.

Materials and Methods

Materials. Diclofenac sodium salt, flurbiprofen, proadifen, α-naphthoflavone, phenytoin (5,5-diphenyl-hydantoin), maleic acid diethyl ester (DEM), 1-buthionine-5R,S,-sulfoximine (BSO), buthylated hydroxytoluene (BHT), deeroxamine mesylate, nifedipine, (±)-verapamil, rhodamine 123, and o-phtaldialdehyde were obtained from Sigma Chemical Co. (St. Louis, MO). Malondialdehyde (MDA bis(dimethylacetal) was obtained from Merck (Darmstadt, Germany). Fluo-3-AM and pluronic F-127 were obtained from Molecular Probes, Inc. (Eugene, OR). β-Glucuronidase/arylsulfatase, collagenase, the Glucose GOD-Perid test, and the ATP bioluminescence were obtained from Boehringer Mannheim (Mannheim, Germany). Calf serum was obtained from Gibco (Paisley, UK), and culture media were obtained from Flow Labs. (Irvine, CA). Diclofenac metabolites (4'-OHdic, 5-OHdic, and 4',5-OHdic) were synthesized as described (Bort et al., 1996). All other reagents used in this study were of analytical grade.

Cell Cultures. MDCK, FaO, and HepG2 cells were cultured in Dulbecco’s minimal essential medium supplemented with 10% of fetal calf serum and containing 50 μg of streptomycin/ml and 50 μU of penicillin/ml. Cells were routinely seeded in 3.5- or 6.5-cm plates at a density of 14 × 10^5 cells in 0.1 ml medium per well and used 24 hr later (75% monolayer confluence).

Rat hepatocytes were obtained from 200- to 300-g Sprague-Dawley male rats by perfusion of the liver with collagenase as described in detail elsewhere (Gómez-Lechón et al., 1984). Human hepatocytes were obtained from small liver biopsies from patients undergoing cholecystectomy, after informed consent. The patients had not received any medication for at least a week before surgery. Cell suspensions were obtained as described in detail elsewhere (Gómez-Lechón et al., 1990). Hepatocytes were seeded on fibronectin-coated culture plates (3.5 g/cm²) at a density of 80 × 10^3 cells/cm². Unattached cells were removed by changing the medium 1 hr after seeding.

Evaluation of Toxicity of Diclofenac to Hepatocytes. Increasing concentrations of the drug in phosphate-buffered saline (PBS) were added to cultures after medium renewal. After a 24-h incubation, microtiter plates were washed twice with 50 μl of PBS/50 μl of PBS, and cytotoxicity was assessed either by measuring the loss of intracellular lactate dehydrogenase (Ponsoda et al., 1991) or by the MTT test (Car- michael et al., 1987).

The effects of diclofenac on gluconeogenesis were investigated in glycogen-depleted hepatocytes incubated with the drug and with lactate as the only gluconeogenic precursor, as described in detail previously (Castell et al., 1985). The gluconeogenic rate was determined from the rate of glucose production by hepatocytes.

The synthesis and secretion of albumin by hepatocytes was monitored by a competitive enzyme-linked immunosorbent assay in aliquots of culture medium taken at regular time intervals (Castell et al., 1985).

Glutathione (GSH) was measured by a fluorometric reaction with o-phthalaldehyde adapted to microscale measurements (Jover et al., 1992). Briefly, cells were detached and homogenized by ultrasound. The resulting homogenates were deproteinized and centrifuged in the same 96-well plate. Aliquots of the supernatant were transferred to microtiter plates and allowed to react with o-phthalaldehyde. Fluorescence was measured in a multiwell plate fluorimeter (excitation filter: 355 ± 35 nm; emission filter: 460 ± 25 nm). Known amounts of GSH (0–5000 pmol/well) were used as reference standards.

Lipid peroxidation was determined by measuring the generation of MDA in the culture media by the fluorometric reaction with thio- barbituric acid (Castell et al., 1997). After incubation for 60 min in a boiling bath, the fluorochrome formed was extracted with n-butanol and the fluorescence of the organic phase was measured at 530 ± 25 nm excitation and 590 ± 35 nm emission. MDA bis(dimethylacetal) diluted in culture medium was used as standard. Results were referred to intracellular protein content.

To monitor intracellular calcium ([Ca++]i), cells previously incubated with diclofenac were loaded with 5 μM of Fluo-3-AM 0.075% (w/v) pluronic F-127 in culture medium for 30 min at 37°C. The cells were washed three times with HEPES-buffered Krebs-Henseleit solution (10 mM HEPES, pH = 7.4, 25°C) containing 1% bovine serum albumin, and immediately thereafter fluorescence was measured with a multwell plate fluorimeter (Cytoflour 2350, Millipore; excitation, 485 ± 22 nm; emission, 530 ± 30 nm) (Jover et al., 1993).

Fluorescence readings were calibrated to calculate [Ca++]i. First the hydrolysed, cytosolic Fluo-3 was released out of cells into medium containing 2 mM CaCl2 by treating cells with 10 mM digitonin for 4 min, and fluorescence (Fmax) was recorded. Next, 10 mM EGTA was added to quench [Ca++]i, and fluorescence (Fmin) was again recorded. [Ca++]i was calculated for any previous fluorescence signal (F) using a Kd of 400 nM for the Fluo-3-Ca complex (Minta et al., 1989), according to the following equation: 

\[ [Ca^{2+}]_i = K_d \times (F - F_{\text{min}}) / (F_{\text{max}} - F) \]

ATP synthesis was determined in cultured hepatocytes incubated in HEPES-buffered saline medium with glucose as the only energetic substrate and 500 μM diclofenac. At regular time intervals, cells were washed with PBS and homogenized in 1 ml of 3% HClO4 at 0°C. Samples were centrifuged (5 min x 9000g) and the supernatant kept at 4°C until analysis. The ATP concentration of the diluted samples was measured using the luciferin/luciferase assay according to the manufacturer’s instructions. Bioluminescence was quantified in a Lumat LB luminescence photometer (Berthold GmbH, Wildbad, Germany).

Mitochond
nm; emission, 523 nm) in a Hitachi F-2000 fluorescence spectropho-
tometer (Hatachi Scientific Instruments, Mountain View, CA).

Isolation of Mitochondria from Rat Liver. Sprague-Dawley rats were euthanized and their livers immediately removed, washed, and homogenized in 4 ml/g ice-cold homogenization buffer (0.25 M sucrose, 5 mM Tris, 1 mM EDTA, pH 7.4). Mitochondria were iso-
lated by centrifugation in sucrose as described elsewhere (Cain and
Skilletter, 1987) and finally resuspended in 0.7 ml of the assay solu-
tion (0.25 M sucrose, 10 mM Tris, 1 mM EDTA, 5 mM KH2PO4, 2 mM
MgCl2, pH 7.4) per gram of liver.

ATP Measurement in Isolated Mitochondria. A mitochon-
drial suspension (final concentration 2 mg/ml protein) containing 2.5
mM ADP and variable concentrations of diclofenac or its metabolites
was preincubated at 30°C for 5 min. Then, substrates were added (2.5
mM glutamate, 2.5 mM malate, final concentration) and after 5 min, 100
µl was taken and dropped on 900 µl of boiling buffer (100 mM
Tris, 4 mM EDTA, pH 7.75). ATP was measured as described above.

Metabolism of Diclofenac. Biotransformation of the drug was
studied both in vitro and in vivo. For in vitro studies, diclofenac was
added to hepatic cultures and incubated for 20 h. Aliquots of
culture medium were enzymatically deconjugated (50 µl of β-glucu-
curonidase/ml, 20 mU of arylsulfatase/ml; acetate buffer 0.1 M, pH
4.5) for 4 h at 37°C. The reaction was stopped by adding acetonitrile
to the samples (1:1, v/v). The resulting precipitate was removed by
centrifugation (10 min, 9000 rpm). The supernatant was diluted with
100 mM phosphate buffer (pH 7.4) to reach 25% (v/v) acetonitrile.
Flurbiprofen (2 µl of a 4.5-mM solution in PBS) was added to sam-
ples as an internal standard.

For in vivo studies, diclofenac was administered i.p. to Sprague-
Dawley rats (40 mg/kg) and urine was collected over cold (0°C)
acetate buffer (0.1 M, pH 4.5) for 4 h at 37°C. The reaction was stopped by adding acetonitrile
to the samples (1:1, v/v). The resulting precipitate was removed by
centrifugation (10 min, 9000 rpm). The supernatant was diluted with
100 mM phosphate buffer (pH 7.4) to reach 25% (v/v) acetonitrile.
Flurbiprofen (2 µl of a 4.5-mM solution in PBS) was added to sam-
ples as an internal standard.

Metabolites were routinely analyzed by high-performance liquid
chromatography (HPLC) in deconjugated and nondeconjugated sam-
ples (Leemann et al., 1993). Samples (20 µl) were injected into a
200 × 4.6-mm C-18 reverse-phase column (Spherisorb ODS 5 µm,
Phase Separations Ltd., Queensferry, UK) furnished with a precol-
culum (ODS 5 µm; 50 × 4.6 mm). The mobile phase (75% triethanol-
amine 0.02% in 100 mM phosphate buffer pH 7.4, 25% acetonitrile)
delivered at 1 ml/min. The column effluent was monitored at 282
nm. Diclofenac eluted at 12.2 min and flurbiprofen at 7.4 min.

Identification of Diclofenac Metabolites. Culture superna-
tants were collected, deconjugated, and extracted with ethyl acetate
either before or after deconjugation. Metabolites were routinely analyzed by high-performance liquid
chromatography (HPLC) in deconjugated and nondeconjugated sam-
ples (Leemann et al., 1993). Samples (20 µl) were injected into a
200 × 4.6-mm C-18 reverse-phase column (Spherisorb ODS 5 µm,
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nm. Diclofenac eluted at 12.2 min and flurbiprofen at 7.4 min.

Results

Cytotoxicity of Diclofenac on Hepatic and Nonhe-
patic Cells. Diclofenac showed a characteristic concentra-
tion-dependent cytotoxicity when added to cultured human or rat hepatocytes, as assessed by the MTT test (Fig. 1).

Similar results were obtained (data not shown) when the
leakage of intracellular lactate dehydrogenase was deter-
mained as a parameter for cell viability. The estimated IC50
values for rat and human hepatocytes (concentration causing
50% cell death) were closely related: 392 ± 34 µM (n = 16)
and 331 ± 7 µM (n = 6), respectively. To elucidate whether these
effects were hepatocyte-specific, cytotoxicity was also
evaluated in human and rat hepatomas, as well as in the
nonhepatic cell line MDCK. Figure 1 shows that hepatoma

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Fig. 1. Cytotoxicity of diclofenac in different cellular systems. Human, rat hepatocytes, rat hepatocytes cultured in the presence of 10 µM pradofien,
and cell lines (FaO, HepG2, and MDCK) were cultured in microwells and
incubated with increasing concentrations of diclofenac. After 24 h, cell
viability was determined by the MTT test. Values are the mean of quin-
tuplicated wells ± S.D. of a representative culture.
The differences in diclofenac toxicity observed in primary cultured hepatocytes, hepatomas, and nonhepatic cells could reflect the different sensitivity of cell lines versus hepatocytes to the drug or to differences in the ability of these cells to metabolize diclofenac. In fact, HPLC analysis of culture medium after a 24-h incubation with a subtoxic concentration of the drug (100 mM) showed that rat and human hepatocytes metabolized diclofenac at similar rates (310 and 340 pmol-min⁻¹-mg⁻¹, respectively), whereas cell lines were unable to metabolize it to a measurable extent (data not shown).

Incubation of rat hepatocytes with a noncytotoxic concentration (10 μM) of proadifen, a broad CYP inhibitor, significantly reduced the toxicity of the drug (IC₅₀: 489 ± 32, p < .005; Fig. 1). Ketoconazole (25 μM), which inhibits the 2C and 3A subfamilies, also reduced diclofenac toxicity significantly (IC₅₀: 514 ± 38, p < .005), whereas α-naphthoflavone-specific CYP1A inhibitor did not apparently modify cytotoxicity (IC₅₀: 392 ± 81, N.S.). Moreover, we found evidence showing a good correlation between cytotoxicity (IC₅₀) and the extent of diclofenac metabolism (r = 0.95, p < .001; Fig. 2).

**Major Biochemical Events in Course of Diclofenac Toxicity.** Analysis of toxicologically relevant biochemical parameters in hepatocytes exposed to diclofenac (GSH levels, lipid peroxidation, changes in [Ca²⁺], and ATP) revealed that upon incubation of cells with toxic concentrations of the drug, no significant accumulation of MDA was found in the medium after several hours. In control experiments, addition of 1 mM t-butyl hydroperoxide resulted in an immediate, dramatic increase in thiobarbituric-reactive substances (Fig. 3A). In agreement with these findings, we did not observe a decrease in toxicity (increased IC₅₀) when cells were incubated with rhodamine 123. Remaining fluorescence in medium was measured fluorimetrically as described in Materials and Methods. For a better interpretation of results, cell viability of the same experiment (LDH) is also depicted. Values represented as mean of five wells ± S.D. of a representative culture.

Diclofenac, however, caused an important, fast depletion of GSH in hepatocytes (GSH levels, lipid peroxidation, changes in [Ca²⁺], and ATP) revealed that upon incubation of cells with toxic concentrations of the drug, no significant accumulation of MDA was found in the medium after several hours. In control experiments, addition of 1 mM t-butyl hydroperoxide resulted in an immediate, dramatic increase in thiobarbituric-reactive substances (Fig. 3A). In agreement with these findings, we did not observe a decrease in toxicity (increased IC₅₀) when cells were incubated with rhodamine 123. Remaining fluorescence in medium was measured fluorimetrically as described in Materials and Methods. For a better interpretation of results, cell viability of the same experiment (LDH) is also depicted. Values represented as mean of five wells ± S.D. of a representative culture.

We also investigated the effects of diclofenac on intracellular GSH levels. An IC₅₀ concentration of diclofenac did not cause significant changes in intracellular GSH during the 5 h following incubation (Fig. 3B). As expected, the presence of BSO caused a rapid GSH depletion in cells. Neither BSO nor DEM (500 μM) increased the toxicity of diclofenac (IC₅₀ = 368 ± 12 and 367 ± 47 μM, respectively, versus control at 392 ± 34 μM).

The possibility that calcium could be involved in the early stages of toxicity by diclofenac was also investigated. The addition of an IC₅₀ concentration of diclofenac did not result in an increase in intracellular [Ca²⁺] during the first 120 min of incubation (Fig. 3C). After much longer incubation times (>6 h), we observed a gradual increase in [Ca²⁺] (ca. 150–200% over controls; data not shown). Addition of 25 μM verapamil or 100 μM nifedipine to culture medium (concentrations effectively blocking calcium influx in cells, Jover et al., 1993) was moderately effective in decreasing diclofenac cytotoxicity (IC₅₀ = 415 ± 92 and 507 ± 30 μM, respectively).
finding, increasing diclofenac in culture medium resulted in a concentration-dependent inhibition of gluconeogenesis and albumin synthesis, two specific hepatic functions that require substantial amounts of ATP. This inhibition was noticeable at subcytotoxic concentrations of diclofenac. The IC$_{50}$ were 110 ± 12 and 108 ± 9 μM, respectively.

**Metabolism of Diclofenac.** Analysis by HPLC of culture media of hepatocytes incubated with diclofenac allowed the identification of several metabolites. A peak with a retention time of 3.8 min was assigned to 4'-OHdic, while the peak with a retention time of 5.1 min was identified as 5-OHdic, by comparison of the UV-, mass-, and $^1$H-NMR spectra of chemically synthesized metabolites. Other minor peaks at 10.4 and 13.5 min were identified as lactams of 4'-OHdic and 5-OHdic.

A minor peak (retention time 2.9 min) was present with variable intensity in the different culture supernatants assayed. This metabolite was found in culture media mainly in its conjugated form (>95%). The compound was analyzed by HPLC-MS and $^1$H NMR, and the most relevant spectral features are summarized in Table 2 and Fig. 4. The molecular ion peak ($M^+$) was at m/z 327, and the presence of isotopic peaks at m/z 329 and 331 confirmed the presence of two Cl. When compared with the mass spectra of diclofenac, the $M^+$ peak of this metabolite suggested the existence of two hydroxy substituents. The $^1$H NMR spectra of the purified metabolite (Table 1) showed the same number of aromatic H (7.4–6.4 m, 6H) and ethylenic H ($\delta$ 3.68 s, 2H, Ar-CH$_2$-COOH) as 5-OHdic, which excludes an aromatic hydroxylation. Interestingly, the displacement to a high field of the signal of H(3), as compared with that recorded for 5-OHdic, points to the proximal N as the site of oxidation. The compound showed the features of an acid and a UV maximum displacement to 268 nm (versus 282 nm, 5-OHdic). Based on these data, we assigned the N$_2$-(OH)$_2$dic structure to this metabolite (Fig. 4).

To exclude an artifactual formation of N$_2$-(OH)$_2$dic in the course of in vitro experiments, its occurrence was investigated in rat urine 20 h after i.p. administration of diclofenac. In control experiments, 5-OHdic was added to urine of untreated rats and processed as described in Materials and Methods. Approximately 28% of the in vivo administered diclofenac was found in urine as hydroxylated metabolites. In addition to 4'-OHdic and 5-OHdic, both in free and conjugated forms, the presence of conjugated N$_2$-(OH)$_2$dic unequivocally demonstrated the cellular formation of this metabolite (Table 3). N$_2$-(OH)$_2$dic is found only as a conjugate, both in culture media and in vivo, and its concentration is greater inside cells than in culture medium (3.2 versus 0.2 μM), which suggests that conjugation may be crucial for this metabolite to escape from the cell. In control experiments, no spontaneous formation of N$_2$-(OH)$_2$dic was observed.

In the experiment shown in Fig. 5, the cytotoxicity of diclofenac (IC$_{50}$) was determined under an array of different incubation conditions (100–750 μM drug in the presence or absence of selective CYP inhibitors) and was correlated with the amount of metabolites formed by cells incubated with 250 μM diclofenac. A poor correlation was observed in the case of the major metabolite 4'-OHdic ($r = 0.52$, Fig. 5A). Conversely, the IC$_{50}$ correlated with 5-OHdic ($r = 0.84$; Fig. 5B) and with N$_2$-(OH)$_2$dic formation ($r = 0.92$; Fig. 5B).

**Effects of Diclofenac and Its Metabolites on Hepatocyte Mitochondrial Function.** According to the results shown in Fig. 4D, the decrease in ATP was an early event in diclofenac toxicity, which could be attributable either to the drug or to any of its metabolites. In view of the fact that ATP depletion was paralleled by a decrease in mitochondrial membrane potential, we investigated the role of diclofenac and each metabolite on mitochondria by monitoring the synthesis of ATP. As shown in Fig. 6, the mitochondrial ATP synthesis was effectively impaired by 30 μM diclofenac (concentration found in the portal blood of rats given the drug...
orally; Tabata et al., 1996), as well as by its hydroxylated metabolites.

Interconversion between 5-OHdic and N,5-(OH)₂dic by Liver Microsomes. We examined whether 5-OHdic and N,5-(OH)₂dic, whose formation correlated with the toxicity of diclofenac, could also indirectly alter the energetic status of cells. Incubation of 5-OHdic with rat liver microsomes in aerobic conditions resulted in the formation of N,5-(OH)₂dic (Fig. 7A), whereas the incubation of N,5-(OH)₂dic in presence of microsomes and NADPH yielded 5-OHdic (Fig. 7B). This reduction did not take place in the absence of either NADPH or microsomes. Most interestingly, when the NADPH content of the incubation mixture was monitored, a biphasic behavior was observed: a rapid NADPH decrease that coincided with the reduction of most N,5-(OH)₂dic to 5-OHdic, followed by a sustained NADPH consumption once the equilibrium between the two metabolites was reached. Under the same experimental conditions, incubation of 4'-OHdic did not result in either metabolism or in NADPH consumption (Fig. 7C).

Discussion

Diclofenac is an anti-inflammatory drug for which a certain number of severe adverse hepatic reactions have been reported (Ciccolunghi et al., 1978; Helfgott et al., 1990; Iveson et al., 1990; Sallie, 1990; Ouellette et al., 1991; Purcell et al., 1991; Scully et al., 1993). Detailed analysis of some individual case reports revealed clinical features that could be compatible with a direct toxic effect of diclofenac (or any of its metabolites), rather than a drug-allergy mechanism (Helfgott et al., 1990; Iveson et al., 1990; Sallie, 1990; Scully et al., 1993). In the present study, we investigated possible linkages between drug metabolism and cell injury to better understand the mechanisms of hepatotoxicity.

Among the several biochemical parameters examined, ATP was the earliest affected by the cytotoxic concentrations in short-term experiments (Fig. 3D). Parallel to this, a decrease in mitochondrial membrane potential was observed. These results, together with the previously reported protective effect of...
fructose on diclofenac toxicity (Ponsoda et al., 1995), lead us to consider a mitochondrial bioenergetic dysfunction to be one of the possible events causing diclofenac toxicity. The fact that subcytotoxic concentrations of diclofenac (100 μM; Tabata et al., 1996), caused a 50% inhibition of two characteristic ATP-consuming hepatocyte functions, namely gluconeogenesis and albumin synthesis, would favor this hypothesis. Both are “service” functions of hepatocytes and have in common the fact that they are not essential for hepatocyte survival but both require substantial amounts of ATP.

On the other hand, the fact that no significant changes in oxidative stress parameters (i.e., GSH and MDA levels) were observed, and the lack of a clear effect on the cytotoxicity of radical scavengers (BHT) and inhibitors of the formation of active oxygen species (deferoxamine), or compounds depleting intracellular GSH (BSO, DEM), did not support the hypothesis that this mechanism is a key event in diclofenac toxicity.

[Ca$^{2+}$]$_i$ levels did not increase during the early stages of cell exposure to diclofenac (Fig. 3C), which is in agreement with previous reports (Schmitz et al., 1995). Only after a longer incubation of cells with diclofenac did [Ca$^{2+}$]$_i$ increase moderately, parallel to a decrease in cell viability. We believe this event may be simply concomitant with cell death, and the slight decrease in cell toxicity (not significant) that we observed agrees with this interpretation. A decrease in ATP impairs plasma membrane and endoplasmic reticulum ATP-dependent calcium pumps and leads to a sustained rise in intracellular free calcium (Nicotera et al., 1992). It is thus conceivable that the decrease in cellular ATP observed in hepatocytes incubated with diclofenac could be at the root of the late [Ca$^{2+}$]$_i$ elevation.

The experiments also revealed a possible link between drug metabolism and toxicity to hepatocytes. Several facts support this assessment. First of all, the ability of cells to metabolize diclofenac (human = rat [mtt] FaO > HepG2 = MDCK) was inversely related to the IC$_{50}$ values, and inhibition of drug metabolism resulted in a decrease in toxicity (Fig. 1). Second, there was a direct correlation between cytotoxicity and the extent of diclofenac metabolism by hepatocytes (Fig. 2). Third, analysis of culture media of hepatocytes revealed more precisely that cytoxicity to hepatocytes was related to the formation of 5-OHdic and N,5-(OH)$_2$dic (Fig. 5B).

The chemical structure of this new metabolite was identified by the combined use of HPLC-MS, $^1$H NMR (Table 1), UV spectra, and chemical data. In a recent article, Miyamoto et al. (1997) reported the formation of an iminoquinone by HOCl oxidation of diclofenac in activated neutrophils. The authors also reported that hepatic microsomes could oxidize 5-OHdic to the same iminoquinone, which was trapped with GSH. This compound shows strong chemical similarities with the one reported in this study: dehydration of N,5-(OH)$_2$dic would render the hypothesized iminoquinone. In fact, a compound showing similar fragments by HPLC-MS (electron impact fragmentation) than those obtained by Miyamoto et al. (1997) using MS-MS, was detected in preparations of N,5-(OH)$_2$dic and in culture media of cells [m/z: 309 (M$^+$), 267, 229, 201, 195, and 166].

The presence of N,5-(OH)$_2$dic in culture medium, as well as in urine of rats given diclofenac, excluded an artifactual, noncellular formation of the metabolite (Table 2). The fact that it appeared only as a conjugate reinforced this hypothesis and could also indicate that this compound escapes from the hepatocyte only after conjugation. Indeed, we have found that the concentration of this metabolite inside cells is approximately 16 times greater than in culture medium.

| TABLE 2 |
| In vitro and in vivo metabolism of diclofenac |

<table>
<thead>
<tr>
<th>Sample</th>
<th>N,5-(OH)$_2$dic</th>
<th>4'-OHdic</th>
<th>5-OHdic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rat hepatocytes</td>
<td>3.2 ± 2.5</td>
<td>59 ± 14</td>
<td>38 ± 17</td>
</tr>
<tr>
<td>Culture media</td>
<td>(100%)$^a$</td>
<td>(56%)</td>
<td>(34%)</td>
</tr>
<tr>
<td>Rat urine</td>
<td>1 ± 0.8</td>
<td>80 ± 24</td>
<td>20 ± 9</td>
</tr>
<tr>
<td></td>
<td>(100%)</td>
<td>(85%)</td>
<td>(66%)</td>
</tr>
</tbody>
</table>

Data represent relative abundance of metabolites in each analyzed sample. $^a$ Data in parentheses represent the approximate percentage of conjugated metabolite.
Despite the fact that ATP is the most relevant biochemical event observed, it is noteworthy that neither N,5-(OH)₂dic nor 5-OHdic showed much higher toxicity to mitochondria than diclofenac, as the data shown in Fig. 5B anticipated. Looking for other possible links between metabolite formation and cytotoxicity, we observed that the hydroxylamine generated by oxidation of 5-OHdic with microsomes (Fig. 7A) could be back-reduced to generate 5-OHdic in the presence of active microsomes and NADPH (Fig. 7B). Cellular enzymes able to carry out both types of reaction are known to exist (Yamada et al., 1988; Clement and Kunze, 1992). If both reactions take place simultaneously, this would allow N,5-(OH)₂dic and 5-OHdic to enter a futile cycle resulting in NADPH oxidation by O₂. This is what the data presented in Fig. 7C suggest: addition of N,5-(OH)₂dic to microsomes resulted first in a rapid decrease in NADPH by the reduction of N,5-(OH)₂dic to 5-OHdic, followed by a sustained decrease in the nucleotide concentration when both metabolites had reached equilibrium (Fig. 7B). This is not the case for 4-OHdic, a metabolite that is not further metabolized by microsomes, and its formation by cells does not apparently correlate with cytotoxicity. The feasibility of this futile cycle is further supported by the fact that N,5-(OH)₂dic tends to accumulate inside the cell. Consequently, in addition to the inhibitory effects that diclofenac and its metabolites show on mitochondrial ATP synthesis, futile depletion of NADPH by 5-OHdic/N,5-(OH)₂dic oxido-reduction could be at the root of the mechanism of hepatocyte toxicity induced by diclofenac.

Variable formation of 5-OHdic and N,5-(OH)₂dic is observed in cultures of hepatocytes from different human donors when incubated with diclofenac, and recent evidence from our laboratory suggests that this could be due to a different expression of CYP2C19, which is involved in the 5-hydroxylation of diclofenac in the liver (R. Bort, submitted for publication). There is great variability in the expression of this enzyme in humans (Relling et al., 1990). It is thus suggestive to speculate that one factor contributing to the idiosyncratic nature of diclofenac hepatotoxicity could be the different expression of the CYPs metabolizing the drug into reactive/toxic metabolites.

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